Molecular and Atomic Hydrogen from Titan in the Outer Kronian Magnetosphere

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INTRODUCTION

The plasma and neutral particle populations in the magnetosphere of Saturn have been the subject of considerable study since the *in situ* observations of the Pioneer 11 and Voyager 1 and 2 spacecraft. The Voyager ion data have been presented in detail by Lazarus and McNutt (1983) and Richardson (1986) and a similar exposition of the electron data has been published by Sittler *et al.* (1983). Eviatar (1984) has discussed the implications of the spatial and compositional structures discovered by the Voyager Plasma Science (PLS) instrument and has shown that the outer boundary of the so-called "plasma mantle" (Krimigis *et al.*,1981) is a magnetohydrodynamic phenomenon, whereas the inner boundary is a result of the dissociative recombination of molecular ions.

More recently, Richardson *et al.* (1986) have modeled in detail the atomic and molecular processes occurring in the tori associated with the inner satellites, Enceladus, Tethys-Dione and Rhea. They find that recombination will limit the tori of Enceladus and Tethys-Dione to the observed densities even in the absence of transport, while at the radial distance of Rhea, transport begins to play a role because of the radial increase of electron temperature which suppresses dissociative recombination. The derived composition differs significantly from that usually assumed. They find a light ion component consisting of 75% protons and

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25% H_2^+ and a heavy ion component made up of roughly equal amounts of O^+, OH^+ and H_2O^+. The sputtering yields of Bar-Nun *et al.* (1985) were used for the corotating thermal ions and those of Lanzerotti *et al.* (1983,1984) and Brown *et al.* (1982) for the energetic particles.

In this paper, we shall carry out a similar analysis for the Titan region of the magnetosphere. Eviatar and Podolak (1983) have performed an analysis involving atomic hydrogen and nitrogen and their respective ions. They used the parameters observed by Voyager, proton and nitrogen ion source strengths and number densities (Bridge *et al.* 1981; Hartle *et al.* 1982) and the density and size of the neutral atomic hydrogen cloud (Broadfoot *et al.* 1981) to find the neutral atomic hydrogen and nitrogen source strengths, the neutral atomic nitrogen number density and the mean plasma radial transport rate. Molecular hydrogen was not included in their model. They found *inter alia* an atomic hydrogen source strength of $2.4 \cdot 10^{27}\ sec^{-1}$, which was consistent with that estimated from the Lyman-α observations of Broadfoot *et al.* (1981).

The escape of molecular hydrogen from Titan was predicted by Hunten (1973,1977). The presence of H_2 in the lower atmosphere of Titan was confirmed by Samuelson *et al.* (1981) who found a mixing ratio relative to N_2 of $(2\pm1)\cdot10^{-3}$. An altitude profile of H_2 density has been calculated for the atmosphere of Titan by Bertaux and Kockarts (1983) who solve the relevant diffusion equation analytically for a spherical isothermal atmosphere. Their calculation leads to the prediction of a diffusion limited escape flux of $2.5\cdot10^9\ cm^{-2}sec^{-1}$ at a Titanocentric distance of 4100 km, which corresponds to a source strength of $5.3\cdot10^{27}\ sec^{-1}$ in the magnetosphere. They find that return flow is negligible and predict an undetected cloud of molecular hydrogen of 100 cm^{-3}, which is five times the observed number density of atomic hydrogen (Broadfoot *et al.* 1981). Yung *et al.* (1984) estimate an escape flux from the photochemical production of H_2 and its chemical stability and predict a value of $7.2\cdot10^9\ cm^{-2}sec^{-1}$.

Ip (1984) estimated the effect on such a cloud of charge exchange with protons of radiation belt energy. He interprets the observation of energetic neutrals outside the magnetosphere (Kirsch *et al.* 1981) to indicate a sink strength of about $5 \cdot 10^{24}\ sec^{-1}$ and thereby finds an upper limit of $10\ cm^{-3}$ for the H_2 density in the ambient magnetosphere in the presence of the Titan source predicted by Hunten (1973,1977).

We shall consider below the implications of the above H_2 and H source strengths for the neutral and plasma composition of the gas populating the outer magnetosphere. We include the full gamut of atomic and transport processes and H source strength. We shall show that the observed plasma density and composition are consistent with an escape rate of H_2 and H no greater than a few times 10^{26} and discuss the implications of this finding for models of the upper atmosphere of Titan.

EQUATIONS AND PARAMETERS OF THE MODEL

The nature and quantity of the matter that Titan injects into the magnetosphere of Saturn can be inferred from the PLS flyby results for the plasma components (Hartle *et al.* 1982) and from the Voyager Ultraviolet Science (UVS) spectrometer and the implied chemistry for the neutrals (Strobel and Shemansky, 1982). Since the PLS instrument which measures mass per unit charge for a given velocity cannot differentiate between the two possible candidates for the role of the ion of mass 28 apparently observed in the Titan plume, N_2^+ *or* H_2CN^+, (Hartle, *et al.* 1982), we have solved the model rate equations for both cases. Although the ion molecules are heavy, their scale heights will be doubled relative to that of their parent neutrals because of ambipolarity. Once they reach the exosphere where the gyrofrequency exceeds the collision rate, they will be readily removed by the corotation electric field (Eviatar and Podolak, 1983). The ambiguity arises from the fact that N_2 is seen in the atmosphere of Titan (Smith *et al.* 1982) which implies the existence of the ion molecule, while H_2CN^+ has been predicted to be the end product of the nitrogen- hydrogen photochemistry expected to take place in Titan's upper atmosphere (Strobel and Shemansky,1982).

In the magnetosphere, the escaped Titanian matter will be subject to various processes. The neutral molecules will be both dissociated and ionized and the neutral atoms ionized by both solar ultraviolet radiation and electron impact. We have ignored dielectronic recombination of atomic ions (Jacobs *et al.* 1979) since at the observed ambient electron temperature of 100 eV (Sittler *et al.* 1983), the rate of this process is essentially zero. All species, both neutral and ionized will participate in charge exchange and ion-atom interchange reactions. For the case of N_2^+ as the heavy ion, the chemistry will lead to the formation of minute amounts of various nitrogen hydrides whereas the only magnetospheric process involving H_2CN^+ is dissociative recombination. The rate equations describing the evolution of the densities of the various species under these processes are of the following four types corresponding to the various particle species, neutral and ionized molecules and atoms:

$$\frac{dn_j^{(m,n)}}{dt}=\frac{F_j^{(m,n)}}{V}-[(\alpha_j+\beta_j)n_e+\eta_j^{(i)}+\eta_j^{(d)}+v\sum_k\sigma_{jk}n_k^{(a+m,i)}]n_j^{(m,n)}. \qquad (1)$$

$$\frac{dn_j^{(m,i)}}{dt}=\frac{F_j^{(m,i)}}{V}+[\alpha_j n_e+\eta_j^{(i)}+v\sum_k\sigma_{jk}n_k^{(a+m,i)}]n_j^{(m,n)} \qquad (2)$$
$$-[\nu+\gamma^m n_e+v\sum_k\sigma_{kj}n_k^{(a+m,n)}(1-\delta_{kj})]n_j^{(m,i)}$$

$$\frac{dn_j^{(a,n)}}{dt}=\frac{F_j^{(a,n)}}{V}-[(\alpha_j+\beta_j)n_e+\eta_j^{(i)}+v\sum_k\sigma_{jk}n_k^{(a+m,i)}]n_j^{(a,m)} \qquad (3)$$

$$\frac{dn_j^{(a,i)}}{dt}=\frac{F_j^{(a,i)}}{V}+[\alpha_j n_e+\eta_j^{(i)}+v\sum_k\sigma_{jk}n_k^{(a+m,i)}]n_j^{(a,n)}-[\nu+v\sum_k\sigma_{kj}n_k^{(a+m,n)}(1-\delta_{kj})]n_j^{(a,i)} \quad (4)$$

where the following notation has been used: The subscripts j and k denote individual species, δ_{kj} is the Kronecker delta, the superscripts (m,n), (m,i), (a,n) and (a,i) denote molecules, neutral and ionized and atoms, neutral and ionized respectively and the superscripts (a+m,n) and (a+m,i) imply that k is to be summed over both atomic and molecular neutral or ionized species. $F_j^{(m,n)}$,$F_j^{(a,n)}$, $F_j^{(m,i)}$ and $F_j^{(a,i)}$ denote the total output of neutral and ionized molecules and atoms from Titan, α_j is the electron impact ionization rate coefficient, β_j the electron impact dissociation rate coefficient, $\eta_j^{(i)}$ the photoionization rate, $\eta_j^{(d)}$ the photodissociation rate, σ_{pq} the charge exchange cross section between neutral p and ion q, v the relative velocity between the reactants taken to be the mean corotation speed, $n_j^{(p,q)}$ the number density of constituent j which is of structure p(m or a) and charge state q(n or i), n_e is the electron density, ν is the plasma transport rate taken to be $2.3 \cdot 10^{-6} sec^{-1}$ (Eviatar and Podolak, 1983) and V is the volume of the torus $\approx 3 \cdot 10^{33} cm^3$.

For the case of N_2^+ chemistry, there will be 12 equations and 8 for the case of H_2CN^+. We solve the equations for each case numerically starting with an empty magnetosphere and continuing until a steady state is reached. The L-dependent parameters used in the model have been averaged over the region from 15 to 25 R_S. The reaction rates, coefficients and cross sections have been gathered from various sources in the published literature and are tabulated in the Appendix along with the source strengths and species for each case.

RESULTS

In Table 1, we compare the Voyager PLS results taken near Titan with the results obtained for each heavy ion identity from the model equations in which the H_2 source strength of Bertaux and Kockarts (1983) and the H source strength of Eviatar and Podolak (1983) have been used. The PLS results were obtained by choosing spectra with unambiguous light ion peaks and fitting the se spectra ~~(assumed to be H^+ or H_2^+) to~~ assuming the light ion peaks are composed of H^+ and H_2^+ with isotropic Maxwellian distributions. The values measured outside of $20 R_S$ have uncertainties of less than 20%. The H_2^+ densities inside of L=17 are to be regarded as upper limits, while the proton densities in this region are accurate to within 10%. It is apparent that the calculated proton and H_2^+ densities greatly exceed those observed. Therefore, it is reasonable to ask what are the maximum hydrogen source strengths that can be accommodated by the observations.

In Figure 1 we plot the proton and H_2^+ densities against the H_2 source strength (normalized to the Bertaux-Kockarts value) for various values of the atomic hydrogen source strength (normalized to the Eviatar-Podolak value) for N_2^+ chemistry. Figure 2 shows the same variables and parameters for the case in which H_2CN^+ is the heavy ion. Since the H_2^+ density turns out to be nearly totally insensitive to the atomic hydrogen source strength, only one curve, the dashed line, was plotted for it.

Comparison of the graphs which are highly similar to one another with Tables 1 and 2 indicates that values of the densities consistent with the Voyager observations can be attained for values of the source strengths about an order of magnitude less than the nominal values. Thus the plasma torus of the Titan region constrains both the atomic and molecular source strengths of Titan to be of the order $4 \cdot 10^{26} sec^{-1}$.

An additional observational constraint that must be satisfied is the observed neutral atomic hydrogen density of about 20 cm^{-3} (Broadfoot *et al.* 1981). It is of interest to attempt to use this constraint as a means of identifying the heavy ion in the Titan plume. Analysis of the Voyager spectra shows that an ion of mass 14 or 28 amu is present in the plume, but not both. Since it is not possible to determine the mass of the heavy ion from the data, we have solved the equations 1-4 for three possible cases, namely N^+, N_2^+ and H_2CN^+ each as the sole heavy ion in the plume, with the source strength of $7.5 \cdot 10^{25} sec^{-1}$. This value is obtained from the PLS observation of a density of 27 $cm-3$ at flyby flowing out from Titan at 14 km/sec. We assume this flux to be coming from the surface of a sphere of radius 4100 km. This ionopause radius was obtained by Eviatar and Podolak (1983) by equating the gyrofrequency to the ion- neutral collision rate. Hartle *et al.* (1982) found an ionopause distance of 4400 km by equating the ion-neutral mean free path to the horizontal flow scale length. We use the hydrogen source strengths, atomic and molecular, of $4 \cdot 10^{26}$ $sec-1$, derived above. The results are shown in Tables 3A, 3B and 3C.

We note that the case of H_2CN^+ predicts a neutral atomic hydrogen density far below that of the other two cases and well below that which is observed. Thus, H_2CN^+ may be eliminated as the plume heavy ion. The cases of N^+ and N_2^+ both predict neutral atomic hydrogen cloud densities that are consistent with observation and cannot be distinguished on the basis of the hydrogen cloud. The density of N_2^+ is very sensitive to the identity of the heavy ion, but unfortunately the maximum density predicted is below the detector threshold of the Voyager PLS instrument. The density of N^+, on the other hand is almost totally insensitive to the identity of the plume heavy ion. This is a result of the fact that most of the ambient atomic nitrogen ions are created by ionization of neutral atomic nitrogen in the magnetosphere, the source strength of which is nearly 20 times that of the plume heavy ion. If we had used the higher neutral atomic nitrogen source strength of $3 \cdot 10^{26}\ sec^{-1}$ proposed by Strobel and Shemansky (1982), the effect would be even more significant. We point out that the use of the source strength computed by Eviatar and Podolak (1983) gives an N^+ density consistent with the heavy ion density observed.

It has been suggested by Barbosa and Eviatar (1986) that ionization and pickup of titanogenic nitrogen followed by subsequent precipitation to the atmosphere might be the source of kronian aurora. In order to supply the needed 200 MW, a neutral nitrogen source strength of $6 \cdot 10^{26}\ sec^{-1}$ would be required for a nitrogen ionization lifetime to $3 \cdot 10^7$ sec, which implies a neutral nitrogen density of 7 cm^{-3}. We have run the case of the Strobel-Shemansky (1982) source strength ($3 \cdot 10^{26}\ sec^{-1}$) and find a density of 4.4 cm^{-3} and a nitrogen lifetime of $4.4 \cdot 10^7\ sec$. This run, the results of which are shown as Table 4 predicts H, H^+ and N^+ density values consistent with observation. In view of the uncertainties inherent in our present knowledge of the magnetosphere of Saturn, the two pictures do not appear to be in conflict.

DISCUSSION

We have shown, within the limits of the accuracy of the parameters used in the model, that the accepted values of the atomic and molecular hydrogen source strengths of Titan exceed, by an order of magnitude, the values that are consistent with the proton and H_2^+ densities observed by the Voyager PLS instrument in the outer magnetosphere of Saturn. The observed source strengths are consistent with the observed neutral atomic hydrogen cloud density. Such a discrepancy is significant and requires a reassessment of the estimations of the source strengths.

In the study of Eviatar and Podolak (1983), only four species, atomic hydrogen and nitrogen and their respective first ions were considered. At that time the PLS data were still in a preliminary state of analysis and it was thought that the densities of ions of mass two and three were below the noise level of the instrument, which placed a firm upper level on them.

The neutral hydrogen and proton densities were fixed at observed values and in the absence of H_2^+ as a reactant and of H_2 as a source of atomic hydrogen via impact and photodissociation, the calculated high source strength of atomic hydrogen appeared to be a consistent result of the model. The arguments given for the neglect of molecular hydrogen in the face of the predicted source strength (Hunten, 1977) were not tested quantitatively until the present study. It is worthy of mention in this context that Strobel and Shemansky (1982) were the first to derive an atomic hydrogen source strength in the range of a few times $10^{26}\ sec^{-1}$ on the basis of the Voyager UVS results.

The discrepancy in the H_2 source strength calculated by Bertaux and Kockarts (1983) may have a variety of sources. They assumed that the diffusion limited flux is equal to the Jeans flux. This, in itself, may be a source of some degree of overestimation of the escape flux. Chamberlain (1969) has found that the Jeans factor, i.e. the ratio of the escape flux to Jeans flux, will be of order 0.5 for hydrogen escaping from a heavy background gas and will depend weakly on the ratio of escape to thermal velocities. This result was confirmed by more sophisticated calculations of Brinkman (1971). The numerical estimate of Bertaux and Kockarts (1983) is, moreover, based on the molecular hydrogen mixing ratio determination of Samuelson *et al.* (1981). Their data analysis based on opacity measurements is somewhat model-dependent and could, in principle, be influenced by uncertainties in the parameters used to derive their results.

In view of the result that the reduced source strengths reproduce the observed magnetosphere densities of H, H^+ and H_2^+, it appears advisable to readdress the question of the abundance and escape flux of hydrogen from the atmosphere of Titan.

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APPENDIX

In this appendix, we present the species, reaction rates of the various processes that take place and the source strengths assumed for the initial calculations. For those reactions for which we could not find published reaction rates, we used the Langevin relation as presented by Gioumousis and Stevenson (1958):

$$k = 2\pi q\left(\frac{\alpha}{\mu}\right)^{1/2} \approx 10^{-9}\ cm^3\ sec^{-1}$$

The photoionization and photodissociation rates were found by taking the cross sections given by Osterbrock (1974) for H and N and by de Jong *et al.* (1980) for H_2 and folding them into the solar spectra of Torr *et al.* (1979) scaled out to Saturn. We average over a solar cycle to obtain the results listed below. The electron impact dissociation rate for molecular hydrogen was obtained from Giguere and Huebner (1978).

In the list of sources for the various rates we use the following abbreviations:

Giguere and Huebner, 1978 GH

Prasad and Huntress, 1980 PH

Gioumousis and Stevenson, 1958 GS

In the list of source strengths the abbreviation PLS refers to values derived from the Plasma Science Experiment on Voyager 1, which flew past Titan.

Source Strengths for the Titan Problem

SPECIES	VALUE sec^{-1}	SOURCE
H	$2.4 \cdot 10^{27}$	Eviatar and Podolak (1983)
N	$7.5 \cdot 10^{25}$	Eviatar and Podolak (1983)
H_2	$4.6 \cdot 10^{27}$	Bertaux and Kockarts (1983)
H^+	$4.0 \cdot 10^{24}$	PLS
N^+	$4.0 \cdot 10^{24}$	PLS
N_2^+	$2.0 \cdot 10^{25}$	PLS

Species for N_2^+ chemistry

1	H
2	N
3	H_2
4	H^+
5	N^+
6	H_2^+
7	H_3^+
8	N_2^+
9	NH^+
10	N_2H^+
11	NH_2^+
12	NH_3^+

Species for H_2CN^+ chemistry

1	H
2	N
3	H_2
4	H^+
5	N^+
6	H_2^+
7	H_3^+
8	H_2CN^+

DISSOCIATION OF MOLECULAR SPECIES

Dissociative Recombination of Molecular Ions

Species	Rate $cm^3 sec^{-1}$	Source
NH^+	$4.8 \cdot 10^{-9}$	GH
H_2^+	$2.4 \cdot 10^{-9}$	PD
H_3^+	$6.3 \cdot 10^{-8}$	Leu *et al.* (1973)
H_3^+	$2.2 \cdot 10^{-9}$	GH
N_2H^+	$2.2 \cdot 10^{-9}$	GH
NH_2^+	$4.8 \cdot 10^{-9}$	GH
NH_3^+	$6.3 \cdot 10^{-9}$	GH
H_2CN^+	$4.8 \cdot 10^{-9}$	GH

Process	Rate
Photodissociation	$4.3 \cdot 10^{-10}\ sec^{-1}$
Electron impact	$5.9 \cdot 10^{-8}\ cm^3\ sec^{-1}$

IONIZATION

Photoionization Rate Coefficients

Species	Value sec^{-1}	Source
H	$6.5 \cdot 10^{-9}$	Computed
N	$7.0 \cdot 10^{-9}$	Computed
H_2	$5.4 \cdot 10^{-10}$	Computed

Electron Impact Ionization Rate Coefficients

Species	Value $cm^3 sec^{-1}$	Source
H	$3.1 \cdot 10^{-8}$	Lotz (1967)
N	$7.9 \cdot 10^{-8}$	Lotz (1967)
H_2	$5.9 \cdot 10^{-8}$	Kieffer (1969)

Charge Exchange Reactions

Neutral H

Reactant	Products	Rate $cm^3 sec^{-1}$	Source
H^+	H^+ + H	$1.6 \cdot 10^{-9}$	Newman *et al.* (1982)
N^+	H^+ + N	$2.5 \cdot 10^{-9}$	Stebbings *et al.* (1960)
H_2^+	$H^+ + H_2$	$2.8 \cdot 10^{-9}$	Massey and Burhop (1952)
H_3^+	$H_2^+ + H_2$	$2.2 \cdot 10^{-9}$	GS
N_2^+	$H^+ + N_2$	$1.0 \cdot 10^{-9}$	Barsuhn (1977)
NH^+	H^+ + NH	$2.0 \cdot 10^{-9}$	GS
N_2H^+	$H^+ + N_2H$	$1.9 \cdot 10^{-9}$	GS
NH_2^+	$H^+ + NH_2$	$2.0 \cdot 10^{-9}$	GS
NH_3^+	$H^+ + NH_3$	$2.0 \cdot 10^{-9}$	GS

Charge Exchange Reactions

Neutral N

Reactant	Products	Rate $cm^3 sec^{-1}$	Source
H^+	$N^+ + H$	$1.1 \cdot 10^{-8}$	Stebbings *et al.* (1960)
N^+	$N^+ + N$	$1.5 \cdot 10^{-8}$	Hasted (1976)
H_2^+	$N^+ + H_2$	$1.0 \cdot 10^{-9}$	GH
H_3^+	$NH_2^+ + H$	$2.0 \cdot 10^{-9}$	PH
N_2^+	$N^+ + N_2$	$1.1 \cdot 10^{-11}$	GH
NH^+	$N_2^+ + H$	$1.3 \cdot 10^{-9}$	PH
NH_2^+	$N_2H^+ + H$	$9.0 \cdot 10^{-11}$	PH

Charge Exchange Reactions

Neutral H_2

H^+	$H_2^+ + \mathrm{H}$	$7.1 \cdot 10^{-10}$	Tawara (1978)
N^+	$H_2^+ + \mathrm{N}$	$4.8 \cdot 10^{-10}$	GH
H_2^+	$H_2^+ + H_2$	$2.2 \cdot 10^{-8}$	Massey and Gilbody (1974)
N_2^+	$N_2H^+ + \mathrm{H}$	$1.7 \cdot 10^{-9}$	GH
NH^+	$NH_2^+ + \mathrm{H}$	$9.5 \cdot 10^{-10}$	GH
N_2H^+	$H_3^+ + N_2$	$5.1 \cdot 10^{-18}$	Albritton (1978)
NH_2^+	$NH_3^+ + \mathrm{H}$	$1.2 \cdot 10^{-10}$	PH
NH_3^+	$NH_4^+ + \mathrm{H}$	$9.7 \cdot 10^{-12}$	GH

Table 1

Voyager 1 proton and H_2^+ densities near Titan

L	$H^+ cm^{-3}$	$H_2^+ cm^{-3}$
22.73	.07	.07
22.65	.12	.10
20.99	.03	.06
20.94	.06	.06
20.89	.03	.09
20.83	.04	.08
20.78	.10	.08
20.75	.05	.09
16.78	.16	.10
16.57	.11	.12
16.38	.15	.09
16.09	.12	.06
15.40	.11	.11

Table 2A

Calculated densities in the Titan Region

Atomic hydrogen source: Eviatar-Podolak

Molecular hydrogen source: Bertaux-Kockarts

N_2^+ as Titan plume heavy ion

Species	Density cm^{-3}
H	30.3
N	.57
H_2	9.04
H^+	.68
N^+	.03
NH^+	$2.1 \cdot 10^{-3}$
H_2^+	.63
N_2^+	$3.0 \cdot 10^{-3}$
H_3^+	.06
N_2H^+	$2.0 \cdot 10^{-6}$
NH_2^+	$7.4 \cdot 10^{-7}$
NH_3^+	$3.5 \cdot 10^{-10}$
Electrons	1.40

Table 2B

Calculated Densities in the Titan Region

Atomic Hydrogen Source: Eviatar-Podolak

Molecular Hydrogen Source: Bertaux-Kockarts

H_2CN^+ as Titan Plume Heavy Ion

Species	Density cm^{-3}
H	18.2
N	.33
H_2	5.2
H^+	.70
N^+	.03
H_2^+	.70
H_3^+	.54
H_2CN^+	.58
Electrons	2.54

Table 3A

Calculated Densities in the Titan Region

Atomic Hydrogen Source: $4 \cdot 10^{26} sec^{-1}$

Molecular Hydrogen Source: $4 \cdot 10^{26} sec^{-1}$

N^+ as Sole Titan Plume Heavy Ion

Species	Density cm^{-3}
H	17.5
N	1.3
H_2	6.6
H^+	.09
N^+	.01
NH^+	$5.0 \cdot 10^{-6}$
H_2^+	.06
N_2^+	$3.5 \cdot 10^{-8}$
H_3^+	$3.7 \cdot 10^{-3}$
N_2H^+	$1.7 \cdot 10^{-10}$
NH_2^+	$1.3 \cdot 10^{-7}$
NH_3^+	$4.6 \cdot 10^{-11}$

Table 3B

Calculated Densities in the Titan Region

Atomic Hydrogen Source Strength: $4 \cdot 10^{26} sec^{-1}$

Molecular Hydrogen Source Strength: $4 \cdot 10^{26^{-1}}$

N_2^+ as Sole Titan Plume Heavy Ion

Species	Density cm^{-3}
H	17.5
N	1.3
H_2	6.6
H^+	.09
N^+	.01
NH^+	$4.5 \cdot 10^{-6}$
H_2^+	.06
N_2^+	$3.7 \cdot 10^{-3}$
H_3^+	$3.7 \cdot 10^{-3}$
N_2H^+	$1.8 \cdot 10^{-6}$
NH_2^+	$1.2 \cdot 10^{-7}$
NH_3^+	$4.2 \cdot 10^{-11}$

Table 3C

Calculated Densities in the Titan Region

Atomic Hydrogen Source Strength: $4 \cdot 10^{26} sec^{-1}$

Molecular Hydrogen Source Strength: $4 \cdot 10^{26} sec - 1$

H_2CN^+ as Sole Titan Plume Heavy Ion

Species	Density cm^{-3}
H	4.2
N	2.2
H_2	.84
H^+	.09
N^+	.01
H_2^+	.06
H_3^+	.01
H_2CN^+	1.2

Table 4

Calculated Densities in the Titan Region

Atomic Hydrogen Source Strength $4 \cdot 10^{26} sec^{-1}$

Molecular Hydrogen Source Strength $4 \cdot 10^{26} sec^{-1}$

Species	Density cm^{-3}
H	16.1
N	4.4
H_2	5.6
H^+	.09
N^+	.05
NH^+	$1.6 \cdot 10^{-4}$
H_2^+	.06
H_3^+	$3.2 \cdot 10^{-3}$
N_2H^+	$1.2 \cdot 10^{-6}$
NH_2^+	$3.6 \cdot 10^{-7}$
NH_3^+	$1.0 \cdot 10^{-10}$
Electrons	.20

Figure 1. Density of molecular and atomic ionized hydrogen as a function of molecular neutral hydrogen source strength with atomic hydrogen source strength as parameter. The plume heavy ion is taken to be N_2^+.

Figure 2. Density of molecular and atomic ionized hydrogen as a function of molecular neutral hydrogen source strength with atomic hydrogen source strength as parameter. The plume heavy ion is taken to be H_2CN^+.

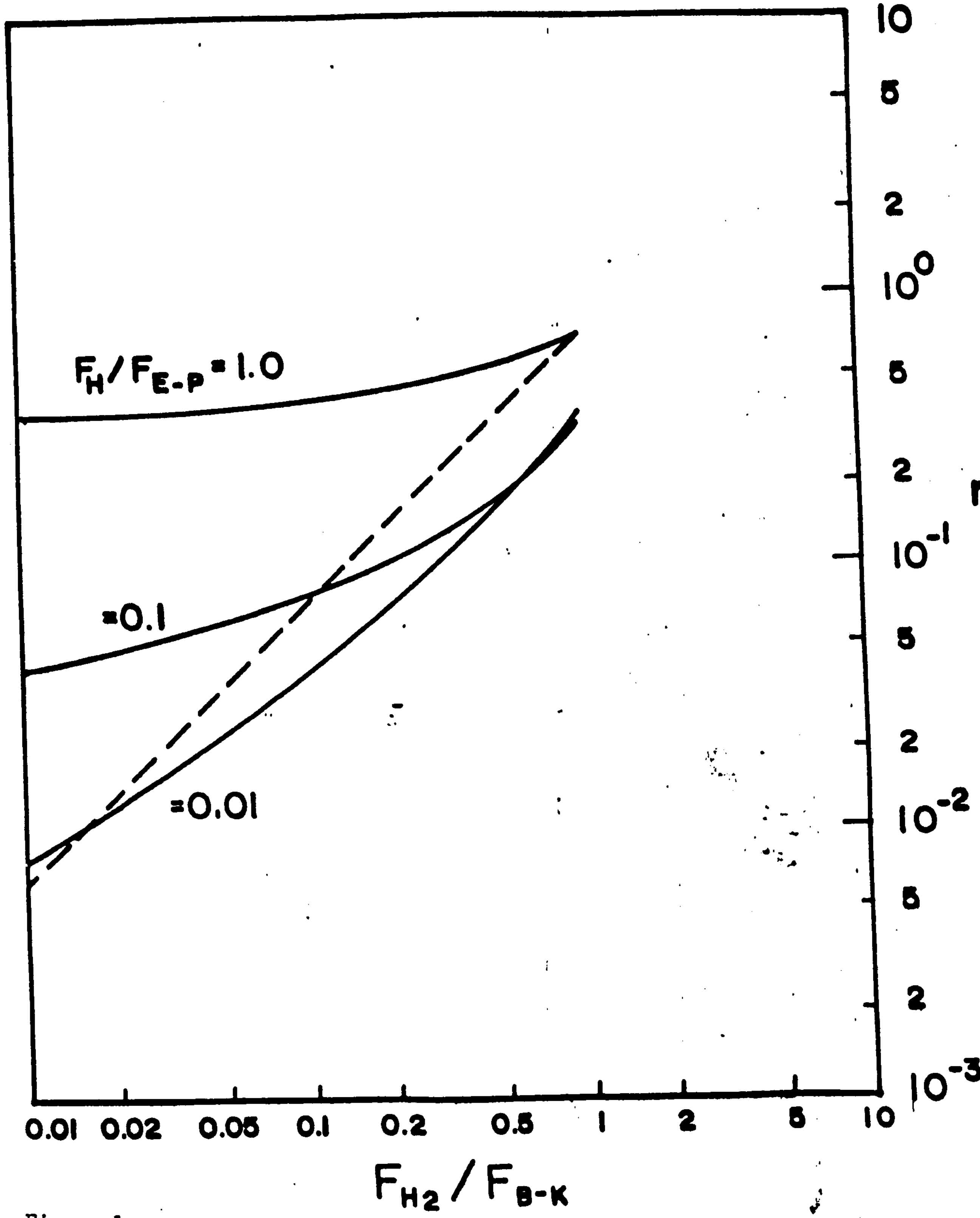
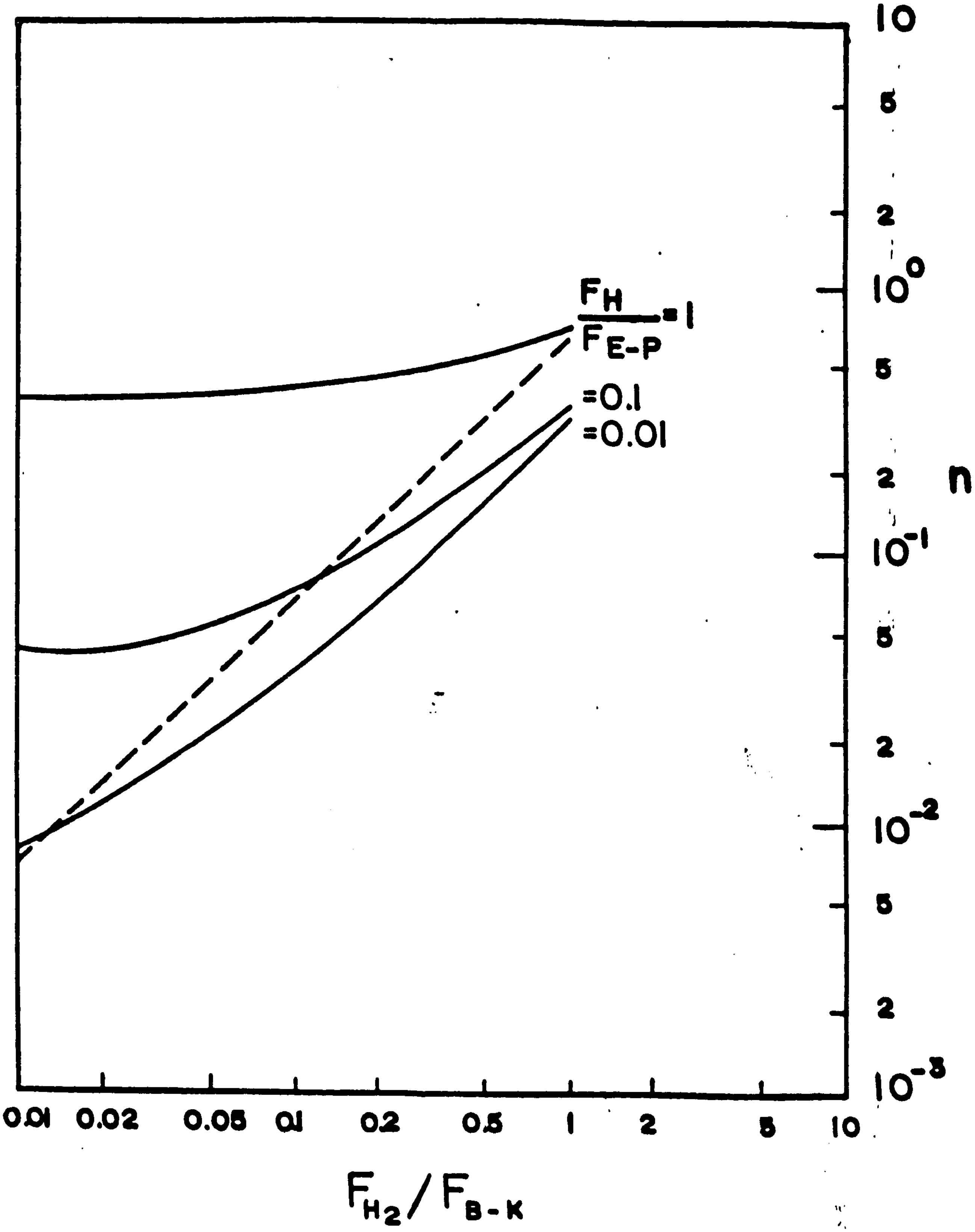

$F_H/F_{E-P} = 1.0$
$= 0.1$
$= 0.01$
10
5
2
10^0
5
2
10^{-1}
5
2
10^{-2}
5
2
10^{-3}
n
0.01
0.02
0.05
0.1
0.2
0.5
1
2
5
10
F_{H_2}/F_{B-K}

Figure 1



10
5
2
10^0
5
2
10^{-1}
5
2
10^{-2}
5
2
10^{-3}
n
$\frac{F_H}{F_{E-P}}=1$
=0.1
=0.01
0.01
0.02
0.05
0.1
0.2
0.5
1
2
5
10
F_{H_2}/F_{B-K}

Figure 2